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Review of Cyclic Varying Pitch Propeller for Commercial Vessels

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ABSTRACT

Typical propellers today are the fixed pitch (FP) and controllable pitch (CP) propeller. With the CP propeller it is possible to pitch all the blades of the propeller at the same time. A cyclic varying pitch (CVP) propeller for commercial vessels is a modification of a CP propeller. With the CVP propeller it is possible to control the pitch of the propeller blades individually. Having the possibility of making a cyclic variation to the blade pitch can yield performance improvements with respect to: efficiency, cavitation, vibrations, pressure pulses and noise. This is because the propeller operates in the wake of the ship. The inflow into the propeller is therefore non-uniform distributed over the propeller, making the operation condition of the individual blade change depending on the blades position in the wake field.

In this paper a review and discussion of the research made so far for the CVP propeller is made. The challenges in realizing the CVP propeller for commercial vessels are identified which constitutes the foundation for future research of the CVP propeller.

Keywords

Cyclic Pitch, Propeller, Wake Field

1 INTRODUCTION

The maritime industry is seeking to decrease the costs of their operations. Especially in the shipping industry which in recent years have experienced a decline in freight rates. The shipping industry are therefore seeking more energy efficient solutions to increase their profit (UNCTAD 2016).

Shipowners are not the only ones that are interested in improving the energy efficiency of their vessels. The international community is also interested in reducing the emission of greenhouse gases, due to global warming, and other polluting gases and particles. The shipping industry where responsible for approximately 2.2% of the global CO_2 emission in 2012 (UNCTAD 2016). The International Maritime Organization (IMO) has made the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) in order to make the shipping industry focus on energy efficient solutions.

The EEDI is a measure of the CO_2 emission to the transported cargo in gram CO_2 per ton mile $[{}^{gCO_2}/_{ton\ mile}]$. A low EEDI is equivalent to a high energy efficiency of the vessel and a high EEDI is equivalent to low energy efficiency of the vessel. Shipowners needs to focus on more energy efficient solutions in order to satisfy the EEDI requirements from IMO. The EEDI reference line is shown in Figure 1 for three types of vessels. From Figure 1 it is seen that the required EEDI of a newbuild vessel decreases over the coming years. For example a new build container carrier with 100.000 DWT build before 2015 may exhaust $\approx 15\,[{}^{gCO_2}\,/\,ton\,mile]$, a container carrier build after 2025 may only exhaust $\approx 10\,[{}^{gCO_2}\,/\,ton\,mile]$.

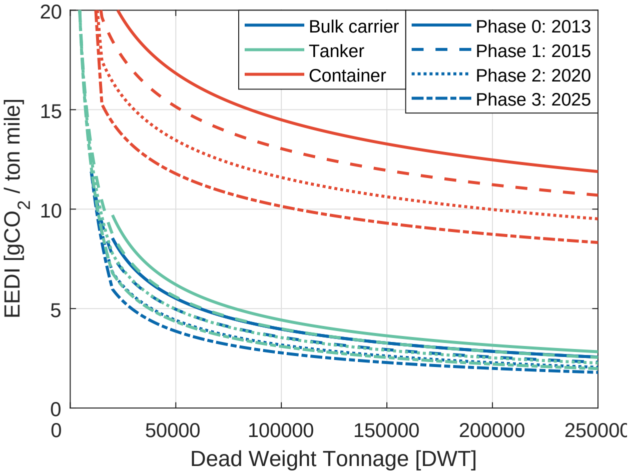

Figure 1: EEDI for bulk carrier, tanker and container based on the data from IMO (2016). The phases gives the year by which the new EEDI requirements are valid for newbuild ships.

Decreasing the EEDI of a vessel also leads to a reduction of emission gases such as NO_x and SO_x and particles. New emission limits are continuously being introduced for the emission of NO_x and SO_x gasses.

Reducing the EEDI of a vessel can be accomplished by many means, like changing the fuel, more efficient engine, more efficient hull design and more efficient propulsion of the vessel. Here, the focus is on the propeller of the vessel.

There exists a number of devices which can improve the efficiency of a propeller. These devices are called energy saving devices and are typically designed together with the propeller because they interact with each other. Most of the energy saving devices either reduces the rotational energy shredded into the water or improves the flow condition for the propeller. The rotational energy shredded into the water does not contribute to the propulsion of the ship and is therefore an energy loss. The improved flow condition may give the possibility of designing more favourable blades for the propeller and thereby increase the efficiency of the propeller. An overview of different energy saving devices and how they increases the efficiency can be found in ITTC (2017b).

The performance of a propeller depends on the propeller design, the ship hull design and the operation conditions. The operation conditions of the ship and the ship hull design influences the flow into the propeller because the propeller operates behind the ship hull i.e. the wake of the ship. The flow field the propeller operates in is called the wake field. An example of the wake field for a single screw ship is shown in Figure 2 as the velocity ratio between the local axial velocity (V_a) of the wake field and the ship speed (V_s). A larger ratio equals a higher axial velocity and a lower ratio equals a lower axial velocity. The axial velocity is the lowest in the wake peak i.e. the 12 o'clock position in Figure 2. The lower axial velocity gives a larger angle of attack and the lift and drag forces on the blade therefore increases in the wake peak. The vectors in Figure 2 are the transverse velocities in the plane.

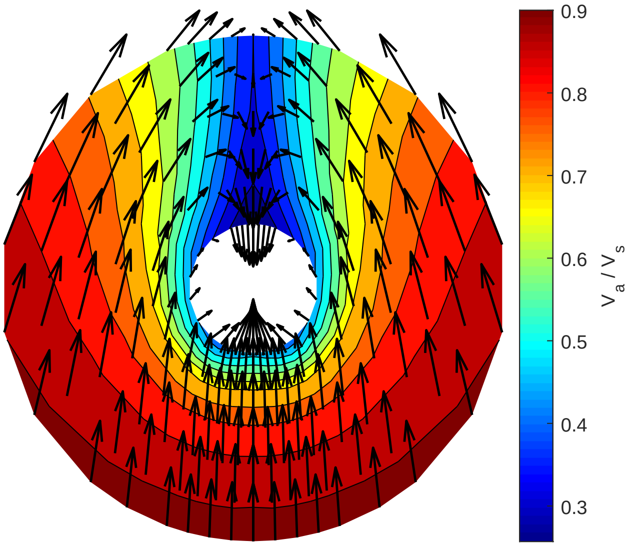

Figure 2: Wake field for a single screw ship.

The wake field shown in Figure 2 is non-uniformly distributed which is generally the case for most ships.The variations in the wake field results in cyclic varying flow conditions for the individual propeller blades as the propeller rotates.

The design engineer has to design the propeller blades such that the propeller satisfies the requirements for the propeller performance. The performance criteria that the engineer has to consider are; the propeller thrust, efficiency, vibrations, pressure pulses, cavitation, noise and reliability.

The focus for the design engineer is to design a propeller that satisfies the requirement for the propeller thrust. The propeller thrust should be large enough in order to propel the ship forward at the desired speed by compensating for ship hull resistance.

The propeller efficiency should be a maximised in order to minimize fuel consumption.

The propeller vibrations are due to the propeller operating in the non-uniform wake field. The varying flow conditions for the blade makes the forces and moments acting on the propeller vary with time. These vibrations can lead to noise and fatigue failures of the mechanical components.

The pressure pulses are due to the interaction between the ship hull and the propeller with a finite number of blades. The passing of the propeller blade close to the ship hull decreases the pressure toward the ship hull which increases again when the blade has passed. The pressure acting on the ship hull therefore varies with time which generates noise inside the ship.

Cavitation of the propeller occurs when the pressure of the water decreases below the vapour pressure whereby the water changes phase from liquid to vapour. Cavitation degrades the performance of the propeller and in the worst case the cavitation can lead to erosion of the propeller. Transient cavitation typically occurs when the propeller blade is in the wake peak.

The propeller noise are due to cavitation and singing (Richardson et al 1998). Furthermore the machinery of the vessel also emits noise. Requirements for the noise depends on the ship type. For merchant ships there are requirements for the noise due to the work environment of the crew and guidelines has been made by IMO (Carlton 2012). For cruise ships and ferries it is desired to minimise the noise in order to ensure a more comfortable trip for the passengers. Research ships have requirements for the noise to minimise the influence on the measurement devices onboard the ship. Naval ships and submarines wants to minimise the noise to make it harder to detect the vessel by sonars etc. It is believed that the noise from ships also influences the life of marine mammals which is why IMO has issued guidelines for the noise emission in order to reduce the impact on the life of marine mammals (IMO 2014).

Reliability of a propeller is a major concern for the owner of the vessel. If the propeller is unreliable, the vessel has to be docked more often and the probability of unexpected breakdown increases. Docking a vessel is expensive and an unexpected breakdown and following docking means that the vessels cannot be in operation. Taking the vessel out of operations means that the owner cannot create a revenue with the vessel in this period and has to cancel contracts on planned work. The fixed pitch (FP) propeller is normally considered to be more reliable than a controllable pitch (CP) propeller. The CP propeller contains more parts which can breakdown and it has a number of parts which moves relative to each other. This introduces wear which over time can make the propeller breakdown.

An alternative to FP and CP propeller is the cyclic varying pitch (CVP) propeller. The CVP propeller may yield performance improvement of the propeller when compared to a FP propeller and a CP propeller. This paper will focus on the CVP propeller as a propulsor and the paper is divided into a number sections. In section 2 the principle of the CVP propeller is described and how the CVP propeller can be used to improve the performance with respect to a

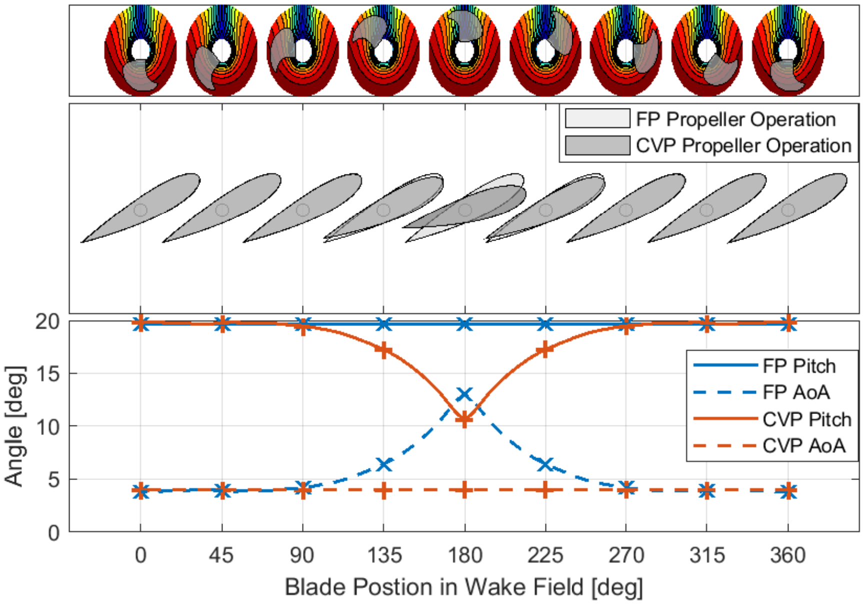

Figure 3: Illustrastion of the operation principle of the CVP propeller.

CP propeller. In section 3 a review is made of the research made so far with the CVP propeller. Based on the review in section 3 a summarization is made in section 4 with respect to the performance of the CVP propeller. In section 5 the challenges, which has not been solved by research so far, in realising the CVP propeller for commercial use are established and discussed.

2 CVP PROPELLER CONCEPT

Common for both the FP and CP propeller is that they are not able to adapt to the local flow conditions in the wake field. This means that the angle of attack varies with the blades position in the wake field, thus introduces some problems such as transient cavitation, increased pressure pulses, increased noise, lower efficiency, shaft vibrations and larger fatigue stresses for the propeller blades.

The CVP propeller is a propeller that is able to adapt the pitch of the individual propeller blades to the local flow conditions in the wake field. The CVP propeller should therefore in principal be able to reduce the transient cavitation, pressure pulses, noise, vibrations and fatigue stresses compared to a FP or CP propeller. It should therefore be possible to design a more efficient propeller. However, the FP propeller may be more efficient than the CVP propeller if a significant larger hub is required for the CVP propeller or more power is required to pitch the blades than is saved. The operation principle of the CVP propeller is shown in Figure 3 for a section of the propeller blade operating in a non-uniform wake field.

Figure 3 is divided into three figures. The top figure shows the wake field of the ship and the position of the blade in the wake field. The middle figure shows the motion of a foil section of the propeller blade for both the FP and CVP propeller. The foil section of the FP propeller blade is fixed during one revolution of the propeller. The foil section of the CVP propeller blade is changing with the blades position in the wake field. The pitch of the foil section for the CVP propeller decreases as the blade comes closer to the wake peak (shown in the center of the figure) and increases after having past the wake peak. This operation for the CVP propeller is repeated for each revolution of the propeller. The bottom figure shows the pitch angle and the angle of attack (AoA) for the foil sections as the propeller rotates in the wake field. It is seen that the pitch of the FP propeller is fixed during a revolution and that the AoA varies. For the CVP propeller it is seen that the pitch angle changes and the AoA is therefore kept constant. This eliminates the issue with transient cavitation, vibrations, etc. The pitch trajectory for the CVP propeller shown in Figure 3 is the pitch trajectory which makes the AoA constant for that section of the blade. This pitch trajectory may not be the same for all the sections of the blade and the optimum pitch trajectory is therefore a trade-off of the performance of all the sections of the propeller blade.

3 REVIEW OF CVP PROPELLER

The idea of a CVP propeller is not new and the idea of cyclic varying pitch is already utilized in other applications. The cyclic varying pitch is already utilized in helicopters, wind turbines and small automated underwater submarines. For the shipping industry no commercially available CVP propeller has been found which is able to pitch the blade individually. However, the CVP propeller has been researched as a potential propulsion for the shipping industry, where different designs have been proposed though the years. These different designs have been divided into four different types/categorises, which are:

- Thrust balanced propeller
- Swash plate propeller
- Passive cyclic varying pitch propeller
- Active cyclic varying pitch propeller

Beside the above four types of CVP propellers there is also the flexible blade propeller. The flexible blade propeller differs from the four above types of CVP propellers by, that the blade deforms to adapt to the local flow condition, where the other CVP propellers pitches the whole blade. The focus of this paper will however be on the CVP propeller which pitches the whole blade and a review of the flexible blade propeller are therefore not included. For the reader interested in the flexible blade propeller, reviews for the flexible blade propeller can be found in ITTC (2002), ITTC (2005), ITTC (2008), ITTC (2011), ITTC (2014) and ITTC (2017a).

3.1 Thrust Balance Propeller

The thrust balance (TB) propeller is a propeller with an even number of blades and it has been proposed and/or discussed in Dubbs (1939), Schoenherr (1966), Pronk (1980), Orbeck (2002) and Takinaci & Atlar (2002). The designs of the TB propeller proposed in Dubbs (1939), Schoenherr (1966), Pronk (1980) and Orbeck (2002) are all similar to each other. An example on the design of a four bladed TB propeller is shown in Figure 4. The blades opposite to each other is connected though the hub by a shaft and the blades is designed such that the center of pressure is placed between the blades spindle axes and its tailing edge. The spindle torque of the blade should therefore always tend to decrease the pitch of the blade.

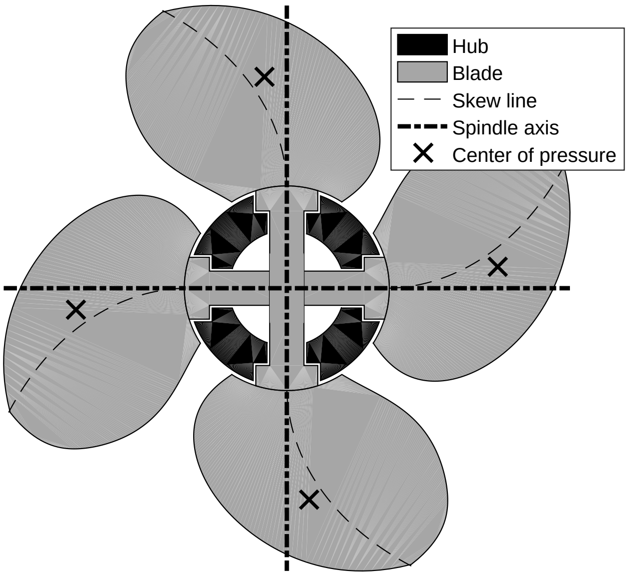

Figure 4: Sketch of a trust balanced propeller (Pronk 1980).

Due to the local velocity variations in the wake field the thrust acting on each blade varies with its position in the wake field. The thrust will have a minimum in the bottom half of the wake field and will increase as the blade moves towards the wake peak where the thrust is at a maximum.

The difference in the thrust on each blade pair results in a torque inequality on the blade pair assembly. This torque inequality will reduce the pitch of the blade in the upper part of the wake field and increase the pitch of the blade in the lower part of the wake field. This reduces the torque inequality of the blade pair assembly until the torque affecting each blade has equalized.

The TB propeller in Dubbs (1939), Schoenherr (1966) and Orbeck (2002) are patents and only presents the mechanical design of the TB propeller. Analysis and performance results are not presented in Dubbs (1939), Schoenherr (1966) and Orbeck (2002) but they postulate on some of the performance improves of the TB propeller. In Dubbs (1939) and Schoenherr (1966) it is postulated that the TB propeller can reduce ship vibration which includes both pressure pulse and shaft vibrations. No comment is given with respect to efficiency, cavitation, noise or reliability. In Orbeck (2002) it is postulated that the TB propeller can increase the propellers efficiency, reduce shaft vibrations, cavitation, pressure pulses and noise. With respect to the reliability in Orbeck (2002) only the blade and shaft are considered. It is postulated in Orbeck (2002) that the blades thickness and shaft diameter can be reduced due to the reduced load variations with the TB propeller. The patent in Orbeck (2002) also include a locking mechanism for the blades which adds the possibility of controlling when the blades can make a cyclic pitching motion.

The study in Pronk (1980) is a theoretical study of the feasibility and performance of the TB propeller. The feasibility study is made to determine whether the blade pitch is able to adapt to the non-uniform wake field to yield a performance improvement. The investigation is made by making a second order dynamical model for the blade pitch motion. The model accounts for the moment of inertia of the blade, the variation in the centrifugal force due to the pitch displacement and the variation in the hydrodynamics due to the pitching motion using Sears (1941). The friction in the blade bearing is neglected. The second order system is excited by the variation in the hydrodynamic spindle torque which is based on measurements. The model is applied to a single propeller design. For this propeller design the maximum difference between the pitch and the hydrodynamic pitch are reduced with 38% during a revolution when using the TB propeller instead of a FP propeller. From these results Pronk (1980) assumes that the propeller efficiency will increase. Furthermore, Pronk (1980) expects the TB propeller to give an improvement in cavitation and that the TB propeller may improve the general vibration level onboard the ship i.e. pressure pulses and shaft vibrations. No direct performance improvement by using the TB propeller is shown in Pronk (1980) they are only inferred based on the reduced maximum variation in the difference between the pitch and the hydrodynamical pitch i.e. AoA.

In Takinaci & Atlar (2002) the performance of the TB propeller proposed in Orbeck (2002) is evaluated. The performance assessment is made with a series of piecewise linear pitch trajectories with the same slope but different pitch offsets. The pitch trajectories are made such that the pitch decreases towards the wake peak and increases towards the bottom of the wake field. All the pitch trajectories has the same amplitude on 6°. The performance of the TB propeller is compared to the same propeller with fixed blades (i.e. a FP propeller), where one of the pitch trajectories has the same mean pitch as the FP propeller. To evaluate the performance of the TB propeller a unsteady lifting surface program is used. The program does not account for the cyclic pitch motion of the blade but do account for the unsteadiness of the non-uniform wake field. To evaluate the performance of the TB propeller a series of evaluation of the performance for FP propellers are made. The FP propellers are all geometric similar except for their pitch, which is displaced for each FP propeller to cover the range of the defined pitch trajectories. The performance evaluation of the TB propeller is made by interpolate the results for the different FP propellers performance using the pitch trajectories. Presentation of the results for the TB propeller mostly focus on the pitch trajectory which has the same mean pitch as the FP propeller. For this pitch trajectory the efficiency is increase by 1.5%, the cavitation is slightly reduced in the wake peak, the pressure pulses are reduced by approx. 50% and the average transverse loads are reduced. Furthermore the propeller thrust and torque are increased. No, direct data are given with respect to shaft vibrations, noise or reliability.

3.2 Swash Plate Propeller

The swash plate propeller uses the same principle utilized in many helicopter rotors to manoeuvre the helicopter. In helicopters a swash plate is used to control the collective pitch and the cyclic pitch of the rotor blades. The collective pitch is the mean pitch for all the blades and the cyclic pitch is a overlying local pitch which depends on the blades position in the rotor field. It is the cyclic pitch that makes the pilot able to steer the helicopter.

In marine propellers the concept with cyclic pitch has primarily been utilized in the cycloidal/VoithSchneider propeller and for autonomous vehicle propulsion (AUV) (Niyomka et al 2013). In AUVs the cyclic pitch is used to manoeuvre the ship/vehicle because the sailing speed is low which makes use of control surfaces such as rudders inefficient. The propeller is normally not used to adapt the pitch to the local velocities in the wake field due to the wake field being more uniform than for single screw ships see Hayati et al (2013).

Utilizing a swash plate propeller for ships are investigated in Simonsson (1981), Simonsson (1983) and Simonsson (1984) and is called the pinnate propeller. The pinnate propeller is shown in Figure 5 and it connects the opposite blade to each other though the hub to minimize friction. To each blade pair two push-pull rods is attached which extends out and makes contact with the swash plate. The swash plate is then angled relative to the propeller shaft in order to get the cyclic pitching of the propeller blades. Using this swash plate principle makes the pitch trajectory sinusoidal.

Propulsion and cavitation model tests with the pinnate propeller where made made in Simonsson (1981) with the sinusoidal pitch trajectory with a minimum pitch $10°$ before the 12 o'clock position due to the phase shift between the pitch change and lift response. Depending on the amplitude (amplitude between $2° - 5°$ with $1°$ increments) of the sinusoidal pitch trajectory either a small loss or a small gain where obtained with the pinnate propeller with respect to a FP propeller. The difference in efficiency where $-0.2\%, -1\%, 0.7\%$ and 0.6% for the different amplitudes which are within the uncertainties of the experiments (Simonsson 1981). The cavitation tests where made with an amplitude on $4.2°$ and under different operation conditions. For all of the operation conditions the cavitation performances where improved in the wake peak but for some conditions the cavitation where more sever in the bottom of the wake field (6 o'clock position). During the cavitation test the pressure pulses was measured at four points on the ship hull. The pressure pulses where reduced by $30 - 45\%$ for all the points when using the pinnate propeller. The tests where made with a modified ship hull which improved the flow conditions for the pinnate propeller and reduced the resistance by 1%. Using the modified hull with the pinnate propeller yielded a 3.6% increase in efficiency compared to using the unmodified ship hull with a FP propeller.

The study in Simonsson (1983) includes the results from Simonsson (1981) and extends upon them experimentally and documents the theoretical considerations made during the study. The cavitation tests are extended with pitch trajectory with amplitudes of $4°, 5.4°, 5.4°$ and $5.4°$ with a minimum pitch at $20°, 0°, 10°$ and $20°$ before the 12 o'clock position, respectively. The cavitation are reduced in the wake peak for all pitch trajectories but with more cavitation at the 6 o'clock position and face cavitation at the 9 o'clock position. For the load analysis measurements for the hydrodynamic loads are used for the steady part and the dynamical part are model by the method in Sears (1941) with compensation for the low aspect ratio of the propeller blades.

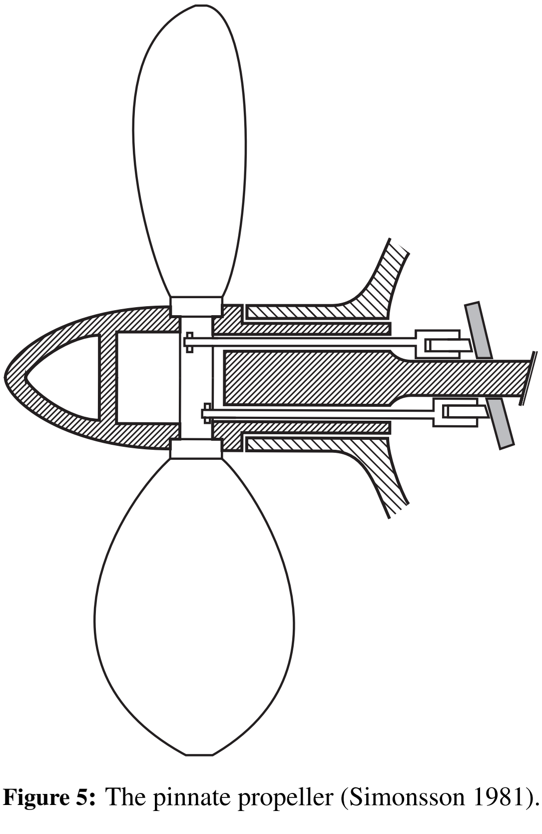

Figure 5: The pinnate propeller (Simonsson 1981).

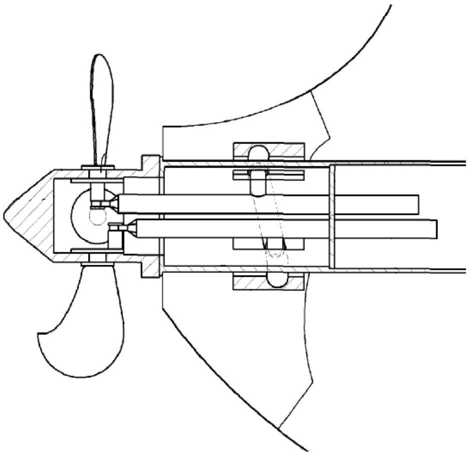

Figure 6: Cam mechanism (Kwun & Kim 2015).

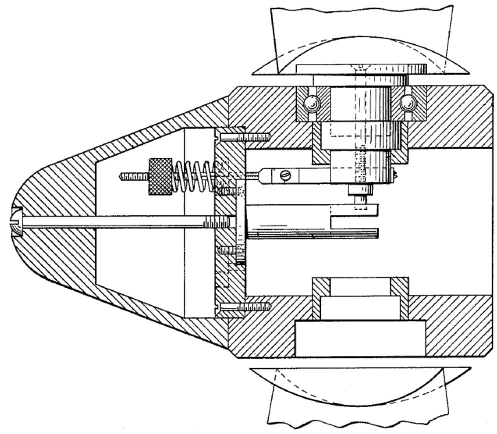

Figure 7: Feathering mechanism (Schoenherr 1966).

The pinnate propeller is tested in full scale in Simonsson (1984) on a Swedish navy patrol boat. The boat has a length of 23 meters, normal service speed of 24 knots and equipped with twin screws on inclined shafts. The propellers are four bladed with a diameter on 0.88 meters. During the test the cavitation in the wake peak where observed and the pressure pulses where measured at four locations. The cavitation is generally reduced with the pinnate propeller and the speed for thrust breakdown due to cavitation where increased by 2 knots. A small increase in efficiency is obtained at high speeds due to the increased speed before thrust breakdown. The pressure pulses are generally reduced by between $1 - 50\%$ when using the pinnate propeller. With respect to reliability the pinnate propeller had some issues during testing. After 500 hours all the seals was replaced due to defective manufacturing which became apparent after 50 hours of testing. In one of the pinnate propellers one of the blade connecting shafts failed due to fatique after approx. $4 \cdot 10^7$ cycles. The test was continued by replacing the pinnate propeller with the original propeller for the ship. The tests ended after the second propeller had operated for approx. $5.5 \cdot 10^7$ cycles. It is postulated in Simonsson (1984) that it is possible by careful design to make a reliable pinnate propeller.

A similar concept to the swash plate is proposed in the patent by Lindahl (1967) which is capable of both collective and cyclic pitching by using a hydraulic transmission system instead of mechanical rods. The cyclic pitching is made by having a hydraulic piston pair for each blade. One of the piston can rotate the blade and the other extends radially out of the propeller shaft inside the ship where it follows a eccentric groove which matches the desired cyclic pitching. Though feedback wires, valves and a collective pitch reference piston a complete collective and cyclic pitching propeller is obtained. It is in Lindahl (1967) postulated that the propeller may reduce the cavitation, shaft vibration, pressure pulses and increase efficiency but no results are shown.

3.3 Passive Cyclic Varying Pitch Propeller

A passive cyclic varying pitch propeller makes the cyclic pitching of the blades by passive components and these components can not be turned on/off. Such systems has been proposed in Schoenherr (1966), Jessup (1976), Bindel (1968), Kwun & Kim (2015) and Hiroshi & Ryosuke (1987).

The passive controlled individual pitch propellers proposed in Schoenherr (1966), Kwun & Kim (2015) and Hiroshi & Ryosuke (1987) are from patents. The concepts proposed in Kwun & Kim (2015) and Hiroshi & Ryosuke (1987) are similar and consist of a fixed guide ring around the propeller shaft with a groove in the guide ring which is formed to the desired pitch trajectory, see Figure 6. Pins extends radial out of the propeller shaft. Pull-push rods inside the propeller shaft which rotates the blades are connected to these radial extending pins. The pins slides in the groove as the propeller rotates thereby making the pitch adjusting to the local velocities in the wake field. It is postulated in Kwun & Kim (2015) and Hiroshi & Ryosuke (1987) that the propeller can be used to improve the efficiency.

In the patent (Schoenherr 1966) a feathering system is proposed using a spring system shown in Figure 7 and having the blades center of pressure being behind the spindle axes. When the blade is in the wake peak the thrust and the spindle torque increases which deforms the spring and decreases the pitch of the blade until an equilibrium in the spindle torque is obtained. When the blade has passed the wake peak the thrust and spindle torque decreases and the pitch increases until an equilibrium in the spindle torque is obtained. In Schoenherr (1966) it is postulated that the propeller can reduce ship vibrations which includes both pressure pulses and shaft vibrations but no analysis or test are shown which supports the statement.

In Jessup (1976) cavitation tests are made with a five bladed propeller, where one of the blades is able to vary the pitch cyclic though a cam mechanism. The propeller was tested in a wake field made by a wake screen which was dominated by second harmonic variations. The pitch trajectory was therefore a second order sinusoidal pitch trajectory. Two cams where made for the tests one with a 7° amplitude and one with a 3.5° amplitude. The cams where tested at four different operation conditions for the 7° amplitude cam and for three operation conditions for the $3.5°$ amplitude cam. For the 7° amplitude cam the transient cavitation was almost eliminated for the pitching blade when compared to the fixed blade for all the operation conditions. For the $3.5°$ amplitude cam the transient cavitation was significantly reduced for all the operation conditions.

In Bindel (1968) cavitation tests are made for a propeller with sinusoidal oscillating blades mounted on a inclined shaft in a uniform flow field. The tests where made in order to reduce cavitation and erosion near the root of the blade. The tests are made for two inclinations of the shaft, amplitudes of the pitch trajectories at 0° and 3° and phase shift of the oscillation at 0° and 30° at different advance coefficients and cavitation numbers. The general tendency of the results was that the oscillating blade in some case could delay the cavitation at the root of the blade, but the cavitation was increased towards the tip.

3.4 Active Cyclic Varying Pitch Propeller

An active CVP propeller is a propeller which uses an actuator and a controller to adjust the pitch of the individual blade to the local velocities in the wake field. By using an actuator one is not limited to one specific pitch trajectory such as in Jessup (1976), Bindel (1968), Kwun & Kim (2015) and Hiroshi & Ryosuke (1987) or specific type of trajectory as in Simonsson (1981), Simonsson (1983), Simonsson (1984) and Lindahl (1967). A active CVP propeller is proposed in Wührer (1985) and illustrated in Figure 8. Similar concepts are also proposed in Thomsen & Freiberg (2015) and Hyuk (2012).

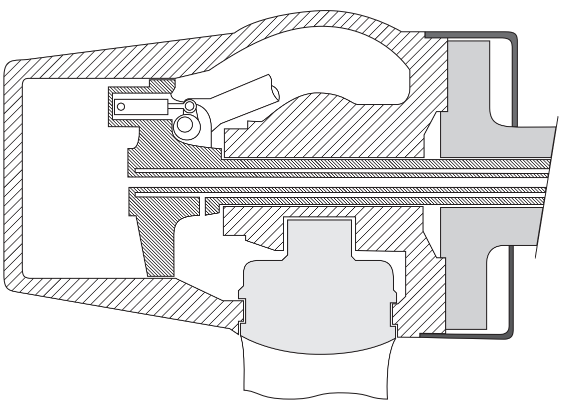

Figure 8: Sketch of the individual blade pitching mechanism proposed in Wührer (1985).

The proposed propeller in Wührer (1985) has the servo piston known from CP propellers which can make the collective pitching of the blades. Smaller servo pistons is attached to the large servo piston which controls the cyclic pitch of the individual blades. Furthermore, it is proposed that the servo pistons can be replaced with a vane actuator or a motor. It is postulated in Wührer (1985) that the propeller can be used to improve the efficiency of the propeller but no results are shown for it. Similarly the patent in Hyuk (2012) proposes the propeller to increase the efficiency.

The performance of an active CVP propeller compared to a FP propeller is made in Gabriel & Atlar (1998). The pitch trajectory is determined in order to remove the time varying components of the axial forces, by using unsteady thin airfoil theory from Sears (1941) and compensating for low aspect ratio of the propeller blades. These theories are linear and by approximating the wake field and pitch trajectory by Fourier series a number of linear equations needs to be solved in order to determine the optimum pitch trajectory.

The performance evaluation of the CVP propeller is made by using an unsteady lifting surface program modified to include the pitching motion of the blade. The propeller used in the evaluation is a five bladed propeller with a diameter of 6.2 meters. The performance of the CVP propeller is compared with the performance of the FP propeller. The performance evaluation shows a 3% increase in efficiency for the CVP propeller compared to the FP propeller due to an increase in the mean thrust. The mean values for the transverse loads are reduced by $8\%-40\%$ for the CVP propeller and the variation in propeller thrust is reduced. The pressure pulses up to the fourth harmonic are determined at five points above the propeller. The pressure pulses are reduced by between $15\% - 60\%$ for the CVP propeller. The extend of the cavitation is generally reduced with the CVP propeller. It is therefore proposed in Gabriel & Atlar (1998) to reduce the area ratio of the propeller to increase the efficiency while maintaining the same cavitation performance as for the FP propeller. But it is not only the thrust and torque which determines the propulsion efficiency given as:

$$\eta_D = \underbrace{\frac{T\, V_a}{\omega_p\, Q}}_{\eta_p} \underbrace{\frac{1-t}{1-w}}_{\eta_h} \tag{1}$$

η_D, η_p and η_h is respectively the propulsion, propeller efficiency and hull efficiency. T is the propeller thrust. V_a is the advance velocity of the water into the propeller. ω is the rotational speed of the propeller. Q is the propeller torque. t is the thrust deduction factor. w is the wake coefficient of the wake field. The wake coefficient and thrust deduction factor for the CVP propeller and an equivalent FP propeller may differ from each other (Gabriel & Atlar 1998).

Reducing the blade area because of the better cavitation performance with CVP propeller have been utilized in an internal investigation at MAN Energy Solutions. The investigation considers a CP propeller with a propeller diameter on 5.4 meters. In this investigation two pitch trajectories where used with the results given in Table 1. The results of the propeller performance is compared with a constant pitch trajectory which is equivalent to the normal operation of a FP and CP propeller. The pitch trajectories used in the internal investigation are shown in Figure 9 as a function of the blades position in the wake field. The 12 o'clock position is equal to a blade position on 180°.

Table 1: Propeller performance from the internal investigation of the CVP propeller at MAN Energy Solutions.

Trajectory	P/D at r/R = 0.7	Thrust per blade [kN]	Power per blade [kW]	η_p	Area ratio
Constant	0.8039	143.0	1506.6	0.5847	0.64
Cosine	0.8098	143.1	1436.0	0.6222	0.57
Variable	0.8144	143.0	1418.5	0.6396	0.50

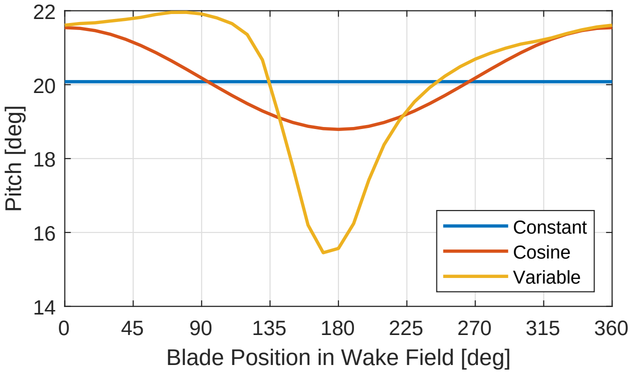

Figure 9: Pitch trajectories for the CVP propeller determined and used in the internal investigation at MAN Energy Solutions.

The investigation has been made such that the average thrust is the same for all the trajectories using a quasi-steady lifting line to evaluate them. The area ratio of the propeller is decreased due to the better cavitation performance and small changes in the blade design where made to ensure an optimum design.

From Table 1 it is seen that the efficiency is increased by 9.4% for the variable pitch trajectory and by 6.4% for the cosine pitch trajectory relative to the constant pitch trajectory.

Thomsen & Freiberg (2015) is a theoretical preliminary study which assess the feasibility of the active CVP propeller by considering the required work to pitch the blades and its influence on the propulsion efficiency. The mechanism considered in Thomsen & Freiberg (2015) is similar to the system proposed in Wührer (1985) by having an individual hydraulic cylinder making the cyclic pitching of the blades. The cylinders and valves are dimensioned such that the blades can be pitched individually according to the pitch trajectories in Figure 9. The cylinders are controlled by proportional valves. Both the cylinders and valves are placed in the hub and it is therefore necessary to extend the hub in the axial direction of the shaft to fit the components into the hub. It was in Thomsen & Freiberg (2015) found that the actuation system lowered the propulsion efficiency for the variable pitch trajectory in Figure 9 but a small increase was obtained in the propulsion efficiency for the cosine pitch trajectory in Figure 9.

4 SUMMARIZATION OF CVP PROPELLER PERFORMANCE

From the above review it is seen that few studies has been made with the focus on the CVP propellers. Many of the ideas are presented in the patents Dubbs (1939), Schoenherr (1966), Orbeck (2002), Lindahl (1967), Kwun & Kim (2015), Hiroshi & Ryosuke (1987), Wührer (1985) and Hyuk (2012). Actual studies is limited to Takinaci & Atlar (2002), Simonsson (1981), Simonsson (1983), Simonsson (1984), Jessup (1976), Bindel (1968), Gabriel & Atlar (1998) and the internal investigation at MAN Energy Solutions. Takinaci & Atlar (2002), Gabriel & Atlar (1998) and the internal investigation at MAN Energy Solutions are theoretical studies, Simonsson (1981), Simonsson (1983), Jessup (1976) and Bindel (1968) are based on model scaled tests and Simonsson (1984) is based on a full scale test. The performance results of the CVP propeller of these studies are summarized in Table 2 which only considers actual performance shown in the studies and not postulated/inferred performance improvements.

From Table 2 it is in general seen that the performance of the CVP propeller is improved compared to a FP propeller.

However, the type of vessel could also have significant influence on the usability of the CVP propeller. If the CVP propeller proves to improve all of the performance parameters in Table 2, then the CVP propeller is suitable for all types vessels if the down payment for the propeller is tolerable and the reliability is reasonable.

If the CVP propeller does not yield an efficiency improvement but only improves the cavitation performance and noise then the type of vessel that the CVP propeller is appropriate for changes. Because an efficiency improvement is not obtained the CVP propeller is not desirable for cargo transporting vessels. The vessels that could still benefit by using the CVP propeller are; navy ships, research vessels, seismic vessels, cruise ships and ferries. These type of vessels typically priorities to some degree having a quiet propulsion system.

An obvious question is then why are the CVP propeller not on the market yet? There are at least two reasons.

The first reason is to consider the energy loss due to the pitching motion of the blades. To assess the feasibility of a CVP propeller to increase the propulsion efficiency, a dynamic model is necessary which accounts for the dynamics of the pitching motion and the actuator system. This has not been considered in any of the above studies except for in Thomsen & Freiberg (2015) which is a preliminary study and the dynamic model used in Thomsen & Freiberg (2015) has to be extended to get more accurate results. By using the dynamic model an optimal pitch trajectory can be found which accounts for the needed work to turn the blades. The dynamic model can also be used to evaluated the feasibility and requirements of different topological designs of the pitching system. Experimental test is needed in order to validate the dynamic model and determine its accuracy. The effect of the CVP propeller on the hull efficiency needs to be investigated. This includes the CVP propellers effect on the thrust deduction factor and the wake coefficient. If the hull efficiency decreases with the CVP propeller then the CVP propeller may only be desirable due to its improved cavitation behaviour.

The second reason is related to the cost of the CVP pro-

Table 2: Summarization of CVP propeller performance excluding the propeller reliability since this has not been investigated in any of the considered work. TB is the thrust balance propeller, SP is the swash plate propeller, PCVP is the passive CVP propeller and ACVP is the active CVP propeller. T is for theoretical studies, MS is model scale testing and FS is full scale testing. *Only considers the variation in the thrust.

	(Takinaci & Atlar 2002)	*(Simonsson 1981)* *(Simonsson 1983)*	*(Simonsson 1984)*	*(Jessup 1976)*	*(Bindel 1968)*	*(Gabriel & Atlar 1998)*	*Internal MAN Energy Solutions Investigation*
CVP propeller concept	TB	SP	SP	PCVP	PCVP	ACVP	ACVP
Efficiency	🟩	🟨	🟩	⬜	⬜	🟩	🟩
Cavitation	🟩	🟨	🟩	🟩	🟥	🟩	🟩
Shaft vibration	⬜	⬜	⬜	⬜	⬜	🟩 *	🟩 *
Pressure pulses	🟩	🟩	🟩	⬜	⬜	🟩	⬜
Noise	⬜	⬜	🟦	⬜	⬜	⬜	⬜
Type of study	T	MS	FS	MS	MS	T	T

🟩	🟨	⬜	🟦	🟥
Improved	May improve	Not investigated or commented	No change	Worsen

peller. The down payment is likely to be larger for the CVP propeller compared to the FP and CP propeller due to the increase complexity of the propeller with the individual pitch mechanism. The efficiency of the propeller should therefore be greater than the efficiency of a FP and CP propeller in order to ensure a reasonable payback time. If this is not the case then the CVP propeller should yield performance improvements compared to the FP and CP propeller which justifies the use of a CVP propeller instead of a FP or CP propeller.

5 CHALLENGES IN CVP PROPELLER

From the above analysis the CVP propeller has the potential to improve the propeller performance when compared to the FP and CP propeller but there are a number of challenges that has to be addressed before the CVP propeller can be used commercially. The challenges in realising the CVP propeller are:

Blade design

How should the propeller blades be designed for the CVP propeller compared to the design rules followed for the FP and CP propeller?

None of the studies (Takinaci & Atlar 2002, Simonsson 1981, Simonsson 1983, Simonsson 1984, Jessup 1976, Bindel 1968, Gabriel & Atlar 1998) considers how the blades for the CVP propeller should be designed. The studies considers an existing blade design and use it for a CVP propeller. The optimum blade design for the CVP propeller is likely to differ from the optimum blade design for the FP and CP propeller. Redesigning the propeller blades for the CVP propeller has been considered in an internal investigation at MAN Energy Solutions. It has to be shown whether the method used in this investigation is an appropriate method to use for the blade design of the CVP propeller before the CVP propeller can be commercialised or if another method is more appropriate.

Pitch trajectory

How should the pitch trajectory be for a CVP propeller to obtain the optimum performance for the propeller?

The pitch trajectory used to investigate the performance of the CVP propeller has in Simonsson (1983), Simonsson (1984), Jessup (1976) and Bindel (1968) been limited to only having the first harmonic or as in Takinaci & Atlar (2002) be piece-wise linear. The performance of the CVP propeller may be limited by using these pitch trajectories. A better performance of the CVP propeller may be obtained when considering pitch trajectories which include several harmonics as in Gabriel & Atlar (1998) and the internal investigation at MAN Energy Solutions. In Gabriel & Atlar (1998) and the internal investigation the pitch trajectories are determined in order to achieve some certain performance criteria for the CVP propeller. It has to be clarified if the methods presented in Gabriel & Atlar (1998) and the internal investigation at MAN Energy Solutions are suitable to determine the pitch trajectory for the CVP propeller. Alternatively, new methods has to be developed to determine the optimum pitch trajectory. The optimum pitch trajectory is likely coupled with the blade design and vice versa. The coupling between these should be investigated and included in the determination of the optimum pitch trajectory and the blade design for the CVP propeller.

Individual blade pitching mechanism

Can a mechanism be designed for the CVP propeller which is able to pitch the blades individually in a cyclic manner during one rotation?

Several different mechanisms for the CVP propeller has been proposed in Dubbs (1939), Schoenherr (1966), Pronk

(1980), Orbeck (2002), Simonsson (1981), Simonsson (1983), Simonsson (1984), Lindahl (1967), Schoenherr (1966), Kwun & Kim (2015), Thomsen & Freiberg (2015), Hiroshi & Ryosuke (1987) and Wührer (1985). Each of these mechanism have their own pros and cons but only the mechanisms, with the limitation of the pitch trajectory to the first harmonic, have been realised Simonsson (1981), Simonsson (1983), Simonsson (1984), Jessup (1976) and Bindel (1968). The only mechanism realised in a real application is Simonsson (1984) which had a couple of breakdowns. The type of mechanisms that can be utilized for the CVP propeller is going to depend on the required loads acting on the blade when it pitches according to the desired pitch trajectory and the propeller size. When having designed the individual pitch mechanism the propulsion efficiency can be evaluated with the power consumption of the individual pitch mechanism included. Then it can be evaluated if an efficiency improvement is obtained with the CVP propeller when compared to a FP and CP propeller.

Reliability

How does the reliability of the CVP propeller change compared to the FP and CP propeller?

The only study that has tested the CVP propeller in an real application is Simonsson (1984). The propeller was tested for almost an year (approx. 55 million cycles) and during this year it experienced a couple of breakdowns which required service of the propeller. In Simonsson (1984) it is believed that a more reliable propeller could be made by reevaluating the design. For commercial application of the CVP propeller, the number of pitch cycles the propeller experience is approx. 1.3 billion for a 20 year lifetime with a rotational speed of the propeller on 120 rpm. This is a large increase compared to the CP propeller which is only exposed to approx. 10 million cycles under similar condition. Wear and fatique of the propeller components are therefore going to be even more significant for the CVP propeller then it is for the CP propeller. It is therefore necessary to investigate how reliable the CVP propeller is and if something can be done to improve the reliability of the CVP propeller. If it is not possible to improve the reliability of the CVP propeller then it may have to be serviced more regularly than a CP propeller.

CONCLUSIONS

Though the paper a review of research made with the CVP propeller is made. The review shows that the CVP propeller has potential to increase the performance of the propeller when compared to a FP and CP propeller. Depending on the performance of the CVP propeller, the type of vessels that the CVP propeller is suitable for varies. If the CVP propeller proves to improve all of the propeller performance parameters then the CVP propeller is suitable for all types vessels if the down payment for the propeller is tolerable and the reliability of the CVP propeller is reasonable.

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